Sediment Acoustics: LF Sound Speed, HF Scattering and Bubble Effects

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Award Number: N00014-06-1-0125
http://www.arlut.utexas.edu/

LONG-TERM GOALS

Physically sound models of acoustic interaction with the ocean floor including penetration, reflection and scattering in support of MCM and ASW needs.

OBJECTIVES

The objectives are to fill important gaps in our knowledge and understanding of ocean sediment acoustics, including (1) a new model to account for the recently measured low-frequency sound speed anomaly, (2) new scattering mechanisms to augment current Navy models of high-frequency bottom scattering, and (3) the study of time dependent propagation and scattering effects due to shallow water gas bubbles in the sediment.

APPROACH

New propagation model development: Previous accomplishments in sediment acoustics include (a) the detection of sub-critical angle penetration (Chotiros 1989, 1995a), (b) the realization that the effective density is less than the physical density (Chotiros 1995b and Williams 2001), (c) the composite medium extension of the Biot model (Chotiros 2002) which gave a better understanding of the boundary between frame and fluid, and (d) the relaxation mechanisms, also known as squirt flow, at the grain-grain contacts (Chotiros, Isakson 2004). There is a recently discovered anomaly that needs to be addressed: the low-frequency sound speed anomaly. Measurements at SAX04 (Hines, Osler, Scrutton, and Lyons, 2005), SAX99 (Williams et al. 2002) and a previous set of measurements by Turgut (Turgut, Yamamoto 1990) show sounds speeds below 2 kHz that are significantly lower than the lower-bound predicted by the Wood equation. One possible cause is the presence of minute gas bubbles in the sediment, which current instrumentation is unable to resolve. Another, and more likely cause, may lie within the dynamics of the skeletal structure.

New bottom scattering model development: Initial measurements in 1960s (McKinney and Anderson 1964) and model studies, indicated that backscattering strength increased with frequency, and this was partially responsible for the frequency selection of the AN/SQQ-32 sonar. But later measurements did not uphold this trend. Measurements in the 1980s lead to the APL-UW HFEVA bottom backscattering model. While this model was well-tuned to the 1980s data, it fit neither the earlier data nor the later data, as well. These observations show that no one measurement, or program of measurements, has been able to capture the diversity of the seabed. A database of all the published measurements is needed to fully comprehend the scope of the problem. As an example of the utility of such a database,

Report Documentation Page

Form Approved
OMB No. 0704-0188

1. REPORT DATE **30 SEP 2006**	2. REPORT TYPE	3. DATES COVERED **00-00-2006 to 00-00-2006**

4. TITLE AND SUBTITLE **Sediment Acoustics: LF Sound Speed, HF Scattering and Bubble Effects**	5a. CONTRACT NUMBER
	5b. GRANT NUMBER
	5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S)	5d. PROJECT NUMBER
	5e. TASK NUMBER
	5f. WORK UNIT NUMBER
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) **University of Texas at Austin,Applied Research Laboratories,P.O. Box 8029,Austin,TX,78713-8029**	8. PERFORMING ORGANIZATION REPORT NUMBER
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)	10. SPONSOR/MONITOR'S ACRONYM(S)
	11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release; distribution unlimited

13. SUPPLEMENTARY NOTES

14. ABSTRACT

15. SUBJECT TERMS

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT **unclassified**	b. ABSTRACT **unclassified**	c. THIS PAGE **unclassified**	**Same as Report (SAR)**	**6**	

data accumulated prior to 1996 was used by the Sonar Optimization Working Group (SOWG) to make informed decisions regarding the appropriate application of current Navy models (Keenan, 2002). For basic research, statistical analysis of the database is expected to reveal hitherto undiscovered scattering mechanisms, and lead to new model development.

Time-dependent effects due to shallow water gas bubbles: Analysis of the HF backscattering database suggests that gas bubbles may be an important scattering mechanism. Previous modeling efforts (Boyle and Chotiros 1995) indicate that very small amounts of gas, less than 100 parts-per-million, may be responsible. New research suggests that shallow water gas bubbles are not a rare occurrence. A recent laboratory experiment, simulating conditions at the SAX99 experiment, suggests that the bubble population varies with sun light, causing daily variations in the backscattering strength of up to 20 dB (Holliday, Greenlaw, Rines, Thistle 2004). Current Navy models do not admit any time-dependent processes.

WORK COMPLETED

Progress was made in the development of a new model for low frequency sound speed and attenuation in water-saturated granular ocean sediments, particularly in relation to the observed sound speed anomaly. An analysis of the mechanical coupling between grains in a randomly packed unconsolidated granular medium showed that the sound and shear wave speeds in such a medium will significantly differ from the values predicted by the standard speed expressions for a uniform elastic solid. A model of the grain contact physics in the presence of a propagating wave was developed for the case of elastic contacts, and extended to include some effects of slippage. The results were compared to extant experimental data.

RESULTS

There are two possible causes for the anomalously low sound speeds measured: gas in the pore fluid, and energy coupling into orthogonal linear and rotational motion at the grain level through contact asymmetry. The former process is well understood, and can be verified by direct measurement of gas content, or indirectly by measurement of sound speed in the pore fluid. The latter is the more difficult and interesting physical process that is expected to be more pervasive. An expression of the sound speed was obtained in terms of the orthogonal coupling coefficients for the case of totally elastic contacts, which indicated that the usual equations for acoustic and shear wave speeds in a uniform elastic solid may overestimate the wave speeds.

A new model of acoustic propagation in granular media was developed based on grain contact physics. Random packing gives rise to contact asymmetry. As a consequence, compared to an elastic solid, there are additional components in the kinetic energy equation, due to orthogonal coupling of linear and angular motion at the grain level. This is unique to granular media. The key points are illustrated with the aid of a two-dimensional arrangement of spherical grains in the figure below. A regular arrangement of five grains, in the equilibrium state, is shown in (a). The grains are spherical and each grain-grain contact region is outlined by a rectangular boundary. Consider the situation where the outer grains are pushed horizontally toward the center grain by external forces. The relative displacements are exaggerated for illustration purposes. There are 4 different classes of deformation, illustrated in (b), (c), (d) and (e).

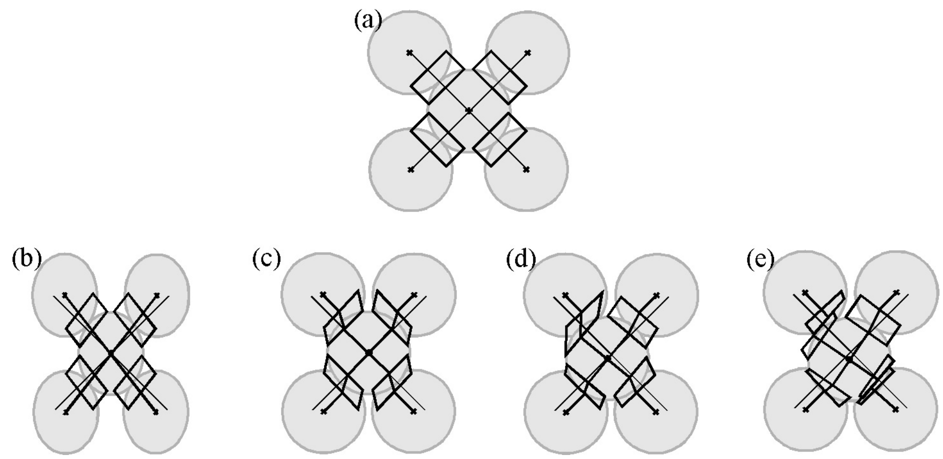

Figure: Illustration of dynamic models for granular media under compression: (a) equilibrium state, (b) uniform, isotropic elastic frame, (c) symmetric elastic contacts, (d) asymmetric elastic contact stiffness, (e) asymmetric contacts with slip.

It is often assumed that the grains form a homogeneous and elastic skeleton. In which case, the strain must be evenly distributed and all parts of the skeleton must deform uniformly. Thus, the grains deform into ovals and the contact rectangles are compressed and slightly sheared, as illustrated in (b). The porosity remains constant. The center grain retains its position in the lattice. The Poisson's ratio of the frame is equal to that of the grain material. This assumption is often used in the application of Biot's theory to the modeling of porous rocks and sandstones (Gazanhes and Hérault 1993, Gal, Dvorkin, Nur 1999), and it is implicit in Stoll's equations (Stoll 1989). This is usually referred to as the uniform, isotropic elastic frame assumption.

The uniform, isotropic elastic frame assumption does not accurately represent granular media because the grains are much stiffer than the contacts. Closer to reality, the grains retain their spherical shape and almost all the strain is absorbed by the contacts, mostly in the form of additional shear deformation, as illustrated in (c). For small strains, this case corresponds to the Hertz-Mindlin model (Mavko, Mukerji, Dvorkin 1998). It predicts a Poisson's ratio for the skeletal structure that is much lower than that of the grain material. The porosity changes as a function of volumetric strain. The center grain still retains its position and orientation, because it was implicitly assumed that the strain is shared equally among all the contacts.

Due to randomness in packing, imperfections in the shape and size of each grain, and random defects on the grain surface, the contact stiffness is expected to vary randomly. Therefore, the strain must be unevenly distributed, as illustrated in (d). The center grain will be subjected to rotation and displacement in random directions. In the illustration, the upper right contact is shown as the stiffest, and consequently the center grain is displaced to the lower left and rotated anti-clockwise. Since the contact stiffness distribution is random, the additional displacement and rotation of each grain must also be random. They represent additional degrees of freedom that will have the effect of absorbing kinetic energy, and increasing the inertia of the system above and beyond its mass density. This case is analogous to a micropolar material (Eringen 1999). This can give rise to the anomalously low wave speeds in granular media. Since all contacts are assumed to be elastic, the process is still lossless.

Finally, if the number of contacts at each grain are more numerous than the minimum necessary to determine its position and attitude, as is often the case, there will be additional stresses due to conflicts between the contact forces. It is reasonable to expect that the weaker contacts may be overcome by the stronger ones, and suffer plastic deformation and slippage. This case is illustrated in (e), in which two contacts are shown as slipped; the contact region is shown as two quadrilaterals with relative slip. The result is an increase in the displacement and rotation of the center grain over and above that of the lossless case. The slippage is also a loss mechanism. Each contact may be modeled as a spring and dash-pot network, and the total frame resembles a complicated Maxwellian system. This process gives rise to wave attenuation that is unique to granular media.

In the context of the wave equation for an equivalent visco-elastic solid, the additional kinetic energy required by the contact stiffness asymmetry may be represented by an apparent increase in the mass density, i.e. a virtual mass. Assuming complete randomness in the contact stiffness distribution, a reduction in sound speed in the region of 5 to 10% relative to the Wood equation is predicted, which is consistent with the existing measurements of low frequency sound speeds in sandy sediments.

IMPACT/APPLICATIONS

The results will impact Navy underwater acoustic propagation models, particularly where reflection of sound from and penetration of sound into the ocean bottom are concerned. It will also impact the future structure of oceanographic databases maintained by Navy offices, including the Naval Oceanographic Office. Predictions of sediment sound speeds may need to be revised. It some cases, the effect on buried mine detection will be dramatic. In one particular instance (Chotiros, Mautner, Løvik, Kristensen, and Bergem 1997), it has been observed that the sediment sound speed changes from being faster than the speed of sound in water to being slower, as the frequency is reduced. In between the extremes, there is frequency range in which the sound speeds are almost perfectly matched, giving low transmission loss and improved buried mine detection performance.

RELATED PROJECTS

This project is closely related to most projects under the Underwater Acoustics: High Frequency Sediment Acoustics Thrust, and the on-going series of sediment acoustics experiments.

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